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Highly Directive Reflect Array Antenna Design for Wireless Power Transfer

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The objective of this study is the design, fabrication, and test of types of broadband reflect-array antenna. Combination of three different element types i.e. single square patch, single square ring and patch loaded ring has been adopted from the literature for application as sub wavelength unit cell(s) to achieve a broadband reflect-array without sacrificing phase range.

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Abstract: The objective of this study is the design, fabrication, and test of types of broadband reflect-array antenna. Combination of three different element types i.e. single square patch, single square ring and patch loaded ring has been adopted from the literature for application as sub wavelength unit cell(s) to achieve a broadband reflect-array without sacrificing phase range. The choice of low-loss substrate materials include PTFE-Norclad and PTFE-Polyglide (compared to FR-4 as standard substrate in widespread use). The fabrication and testing was accomplished using in-house and IITB research partner facilities.

As an extension of the design effort noted above, we have also investigated scaled-up, meta-surface reflect-array in THz regime (0.3-10 THz). This has required adoption of new materials (SU-8, PDMS as dielectric and Au, Al as metal) as well as fabrication processes (micro machining, thin film deposiiton). Finally, testing of such structures has required development of specialized THz-Time Domain Spectroscopy set-up which was accomplished using IITB research partner facilities.

List of Publications:

Journal Publications (under review)

1. A Pattanayak and SP Duttagupta, "A Novel Broadband Reflect-array Design with sub-wavelength ring resonators," communicated to Microwave and Optical Technology Letters

Patent applications (under review)

1. A Pattanayak , SP Duttagupta, PS Gandhi, G Rana, Suryaprakash, S Duttagupta and M Nambia, "RF pencil beam for precision temperature probe application," approval from IIT Bombay for submission to (1) Indian Patent Office and (2) US Patent Office

International Conferences (peer-reviewed, accepted for publication)

1. A Pattanayak and SP Duttagupta, "A broadband reflect-array with combination of sub-wavelength phasing elements," in Asia Pacific Microwave Conference (IEEE-APMC) New Delhi, India, December 6, 2016
2. A Pattanayak and SP Duttagupta, "Materials and Devices for Pencil Beam Generation in RF and THz," in *International Conference on New Scintillations on Materials Horizon (ICNSMH-2016),* Bareilly, India, 23 October 2016 (Invited Talk)
3. A Pattanayak and SP Duttagupta, "Design of Tera Hertz reflect-array antenna using combination of different unit cell elements," in International Conference on Computer Technology, Mumbai, India 2016
4. R Bhadresha, J Sukham, A Pattanayak, G Rana, P Deshmukh, SS Prabhu, and SP Duttagupta, "Tera Hertz bandpass filter based on sub-wavelength apertures in micro-scale thin metal films" in International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Hong Kong, August 24, 2015

Motivation: Reflect-array antenna (RAA) is a planar version of a parabolic reflector as shown in Figure 1. There are certain advantages of a planar RAA vis-à-vis the standard 3-D parabolic design. These include suitability for manufacturing, ease of testing, and flexibility of RAA design for different frequencies.

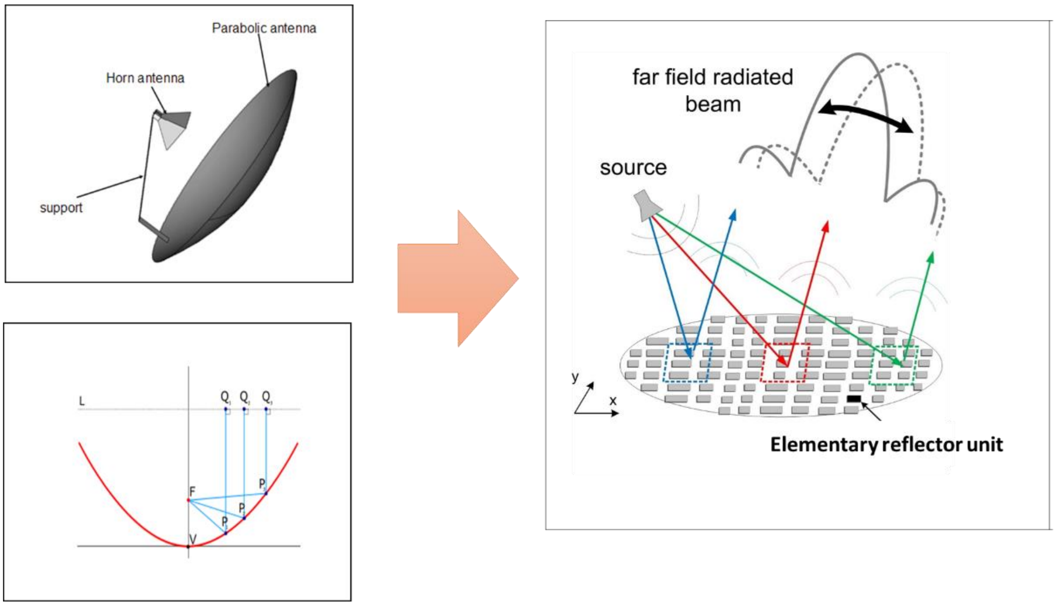

Figure 1. Parabolic reflector and reflectarray antenna

In case of parabolic reflector, the incident beam radiating from the feeding horn impinges on a 3-D curved structure at different angles for different points. The curvature of the structure is adjusted such that all the reflected beams travel in parallel to each other leading to a directional beam. In contrast, for a planar reflect-array antenna the propagation constant vectors of reflected beams are adjusted from reflection phase of each reflector units such that beams are directed to a particular direction. Figure 2 illustrates the design principle of an RAA. A typical reflection phase graph as shown in Figure 2 (a) is obtained from varying the resonance dimension of a unit cell parameter [1]. A particular unit cell located at (x_i , y_i) possesses a reflection phase of Φ obtained from the equation:

$$\Phi = K_0 \, [di - \{ x_i \cos (\Psi_b) + y_i \sin (\Psi_b) \} \sin (\Theta_b)]$$

$$d_i = \{(x_i - x_f)^2 + (y_i - y_f)^2 + (z_i - z_f)^2\}^{1/2}$$

Where Ψ_b and Θ_b are azimuthal and elevation angles of a 3-D spherical coordinate system with reflectarray antenna placed at Θ_b = 90 degree plane; d_i is the separation between feed horn and corresponding unit cell. Once reflection phase is calculated at a particular coordinate corresponding unitcell obtained from reflection phase graph and placed at that position.

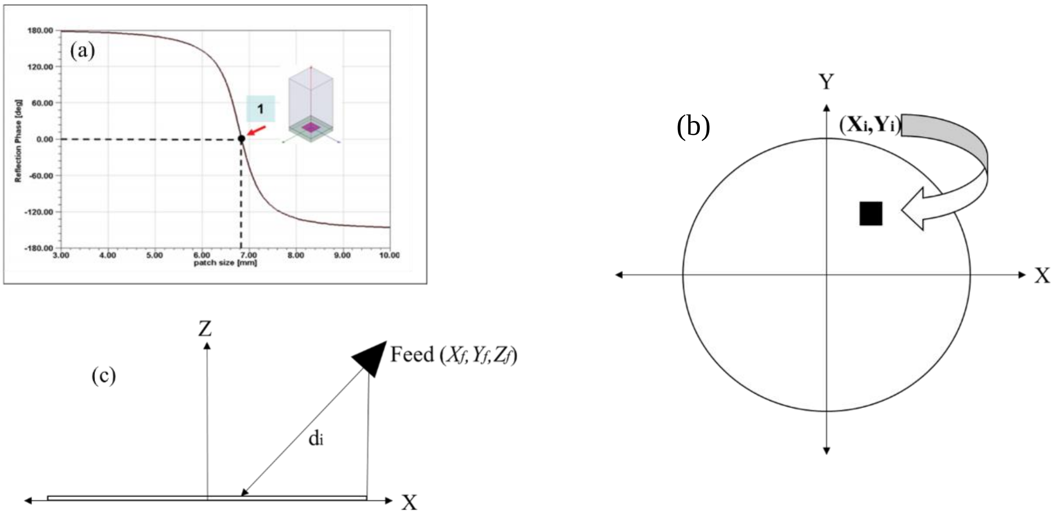

Figure 2: (a) a typical reflection phase graph; (b) unitcell position; (c) feed position w.r.t reflectarray

The reflection phase graph is the key to an optimized RAA design. The two main parameters of the reflection phase graph are phase range and phase sensitivity. A phase range of at least 360^o is required to avoid phase error. Also, phase sensitivity (units: degree / mm) should be as low as possible to avoid fabrication error [2]. However there is a trade-off between phase range and phase sensitivity. Low dielectric constant and thicker substrate help reduce phase sensitivity (desirable). However, phase range is reduced as well (undesirable). The best phase sensitivity reported so far by Yoon *et. al.* [3] is ~200^o / mm with a phase range of 360^o.

Design and Simulation: A broadband reflectarray antenna consisting of different unit cell element types has been designed. Combination of three different element types i.e. single square patch, single square ring and patch loaded ring has been adopted from [4] for studying them in sub wavelength unit cell to get a broadband reflectarray without sacrificing phase range or increasing slope in reflection phase graph. CST Microwave Studio has been employed for both unit cell and full array simulation. Unit cells are shown in Figure 3.

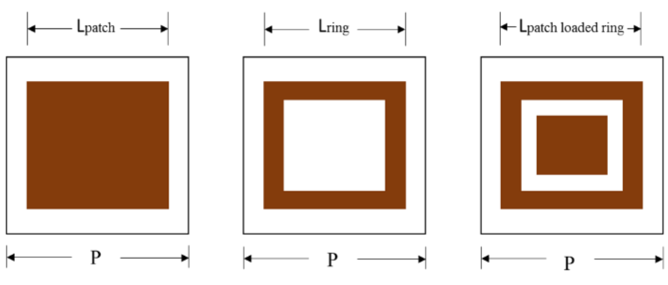

Figure 3: Different unit cell types

Figure 4 shows the reflection phase graphs of different phasing elements for grid spacing of $\lambda/2$, $\lambda/3$ and $\lambda/4$ respectively. As single square elements cannot cover the minimum required phase range of 360^o, the rest of phase range has been covered by single ring and then patch loaded ring element as described in [4]. Parts of phase range covered by three phasing

elements are illustrated as black for single square patch, red for ring and blue for patch loaded ring in Figure 4. Similarly phase angle graphs for three different frequencies have been depicted as solid (4GHz), dashed (5GHz), and dotted (6 GHz) lines respectively.

Comparing Figure 4(a), 4(b), and 4(c) significant improvement of linearization of phase graphs is observed for grid spacing λ/4 as compared to λ/2 and λ/3. However, for λ/4 grid spacing the total reflection phase angle range does not exceed 360° which is minimum required phase range to design a reflectarray antenna without introducing phase error. Thus it is concluded that broadband behaviour for λ/4 grid spacing has been achieved at the cost of phase error which will in turn reduce RAA gain.

In order to resolve this problem an optimum grid spacing of 0.28λ has been selected to design the reflectarray which is slightly higher than 0.25λ and also has covered full 360^0 phase range. Reflection phase varied as a function of outermost length of different phasing elements for 0.28λ grid spacing is plotted in Figure 5. The spectral responses of reflection loss for three phasing elements are plotted in Figure 6. The plot shows that the maximum reflection losses for phasing elements used in reflectarray design element is less than -0.06 dB.

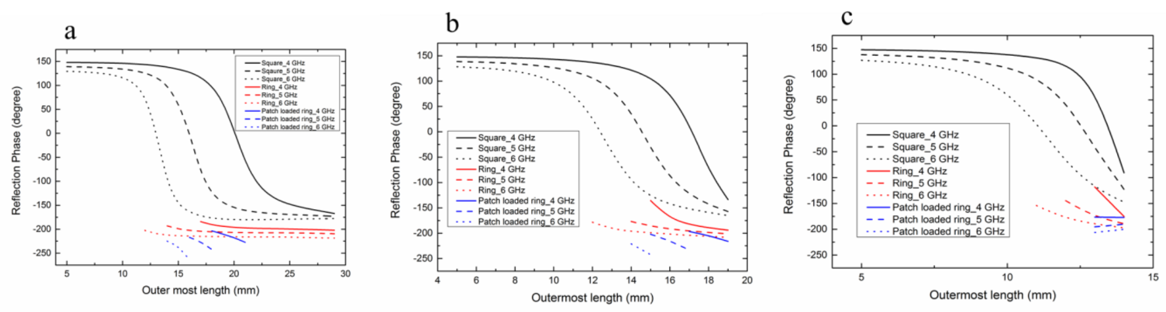

Figure 4: Reflection phase response for unit cell of grid spacing (a) λ/2; (b) λ/3; (c) λ/4

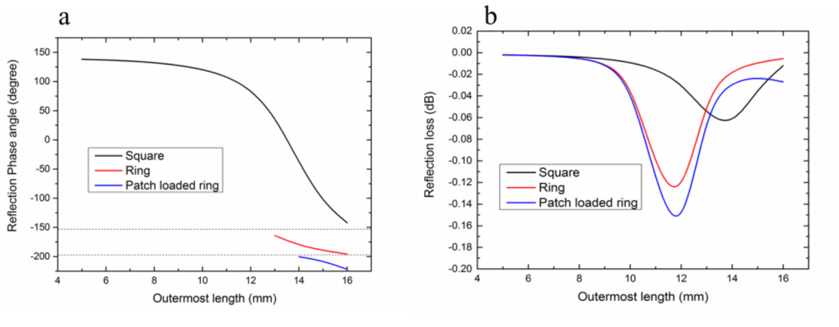

Figure 5: (a) Reflection phase graph for 0.28λ; (b) Reflection loss magnitude

We also address a novel design of reflectarray antenna consisting of a two sets of unitcell to reduce phase sensitivity further with full 360^0 range. The simulation work has been performed by CST MWS® to optimize the reflection phase of the unit cell. FEM based frequency domain solver has been used for this purpose. Various types of substrate is being simulated and tested for reduction of loss. After reflection phase optimisation full array has been designed by a MATLAB code to place each unitcell at their proper position on full array environment and then finally simulated using MoM based IE solver in high performance server with 64 GB RAM which took almost 3 hour to complete a full array simulation.

Fabrication and Testing: Three types of substrate have been used to optimize loss and get highest possible gain. The name of substrates with their corresponding epsilons, loss tangents and thicknesses are enlisted in the table below.

Name of substrate	Epsilon	Loss tangent	Thickness
FR-4	4.8	0.017	1.60 mm
PTFE-Norclad	2.55	0.0011	3.175 mm
PTFE-Polyglide	2.32	0.0005	3.175 mm

At first step the design has been taken from a report [4] as a conceptual test for understanding the principle of the reflectarray design, though in report it was operated at 15 GHz, we have scaled down the design for 5 GHz and also used sub-wavelength unit cells. We further optimize the focal length (F) / maximum dimension (D) to achieve maximum gain and low side lobe level. The first fabricated prototype on FR-4 has been shown in figure 6.

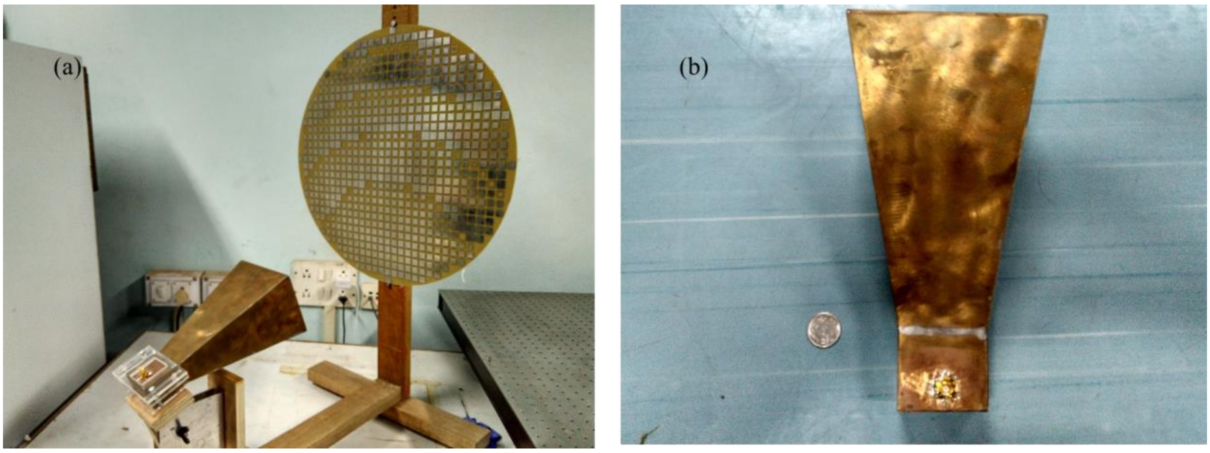

Figure 6: (a) fabricated prototype on FR-4; (b) enlarged image of feeding horn antenna

Then a slight changed design has been fabricated on a PTFE Norclad substrate whose figure is shown below in figure 7.

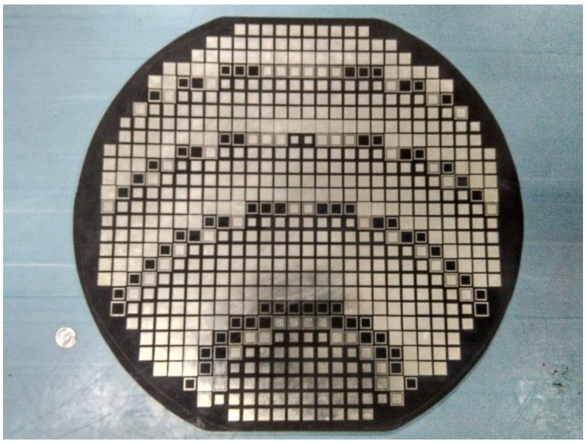

Figure 7: fabricated prototype on PTFE-Norclad

As a final step a novel designed broadband reflectarray has been fabricated on PTFE-Polyglide substrate and tested using a signal generator connected to a broadband horn antenna to generate plane wave at 5 GHz and a spectrum analyser connected to AUT. The measured results show a very good agreement of simulated result.

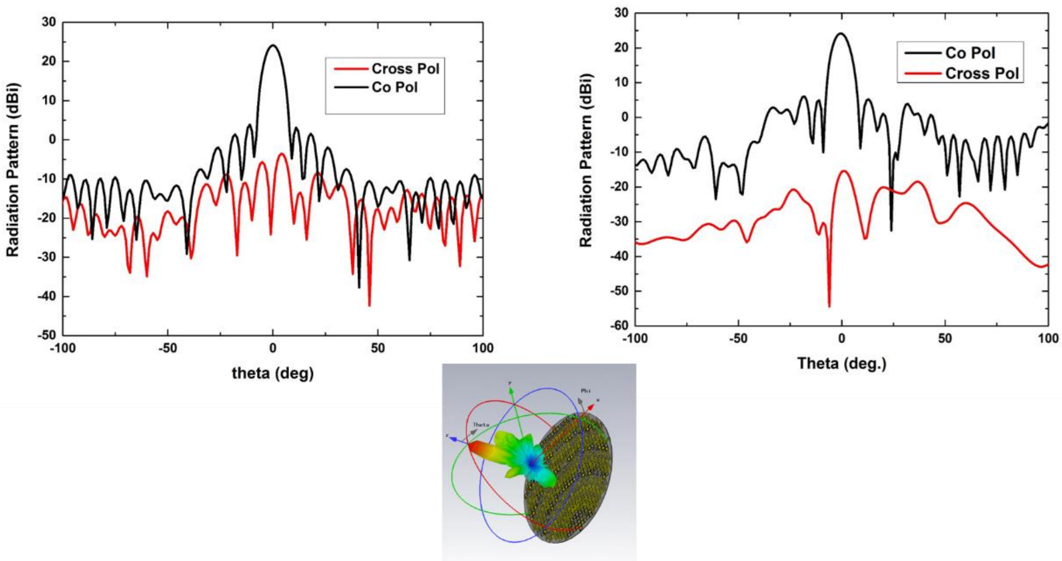

Figure 8: simulated radiation pattern

Table: Simulated radiation pattern (Figure 8) in two principle planes

Plane	Gain (dBi)	SLL (dB)	3-dB beamwidth
Φ = 0 degree	24.8	-18.2	7 degree
Φ = 90 degree	25	-15.3	8 degree

The RAA test setup is show in Figure 9. The RAA test results are shown in Figure 10.

Figure 9: (a) AUT connected with spectrum analizer; (b) Reference horn antenna connected with transmitter

The final array has shown higher gain i.e. 25 dBi compared to previous designed array which had gain of 20 dBi. This increase of gain due to use of less lossy substrate compared to previous substrate and also f/D ratio has been optimized for all three designs. The array consists of total 545 unit cells arranged in 2-D matrix of 30 x 30. The feeding horn antenna is designed and fabricated to operate at 5 GHz. The feed is placed as an offset feed with f/D ratio as 0.75.

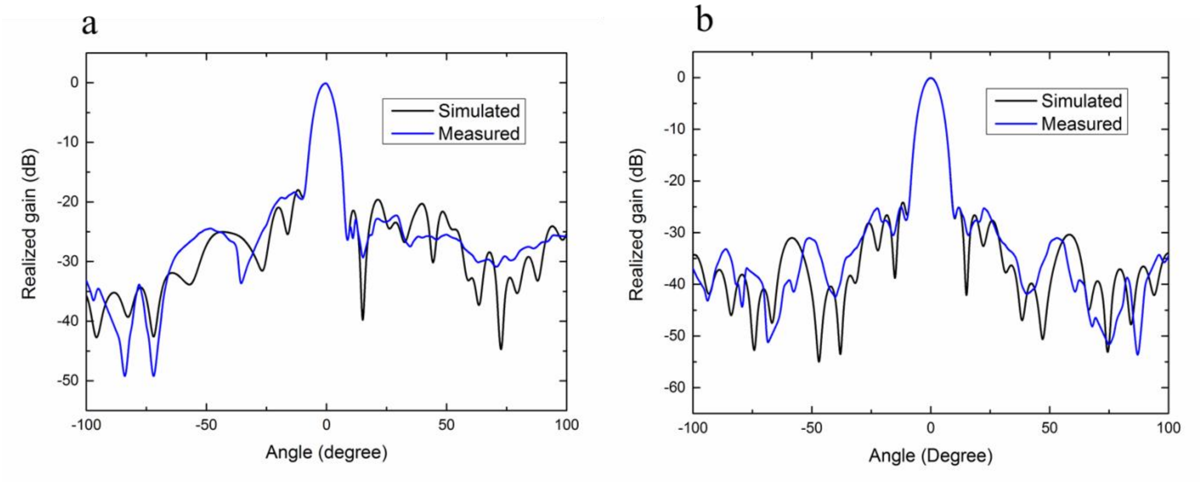

Figure 10: Comparison between measured and simulated result

Conclusion: A novel reflectarray antenna consisting of optimized set of unit cells to reduce phase error and phase sensitivity, operated at 5 GHz has been designed and tested. Measured result supports the simulated result which shows a high gain i.e. about 25 dBi in both planes with 7 and 8 degree 3-dB beamwidth respectively.

References:

[1] Bialkowski et al. IEEE Transactions on Antennas and Propagation, November 2008

[2] Rajagopalan et al., IEEE Antennas and Propagation Magazine, October 2012

[3] Yoon et al., IEEE Transactions on Antennas and Propagation, February 2015

[4] Yoon et al., Electronics Letters, April 2014

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